Mid-Frequency Sonar Interactions with Beaked Whales

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LONG-TERM GOALS

The top-level goal of this project is to build an interactive online modeling and visualization system, called the Virtual Beaked Whale, to enable users to predict mid-frequency sonar-induced acoustic fields inside beaked whales and other marine mammals. Another high-level goal is to acquire new

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14. ABSTRACT
The top-level goal of this project is to build an interactive online modeling and visualization system, called the Virtual Beaked Whale, to enable users to predict mid-frequency sonar-induced acoustic fields inside beaked whales and other marine mammals. Another high-level goal is to acquire new high-resolution morphometric and physical-property data on beaked whales for use in the model. It is hoped that the availability of such a system, together with high-quality data, will give researchers insight into the nature of sonar interactions with beaked whales, and may prove useful in evaluating alternate sonar transmit signals that retain the required information content but with less effect.

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OBJECTIVES

To achieve the long-term goals, a number of scientific and technological objectives have been identified. These include extending existing finite-element-method (FEM) code to describe acoustic interactions with structures, and applying this to a virtual beaked whale and mid-sonar frequencies in the range 1-10 kHz; collecting high-resolution morphometric data through computerized tomography (CT) scans on marine mammal carcasses, and constructing finite-element models of the anatomy; assigning physical properties of tissues; benchmarking the finite-element code; and incorporating the extended finite-element code and morphometric and physical-property data in an online modeling and visualization system called the Virtual Beaked Whale.

APPROACH

The approach and work plan follow an integrated set of six tasks, which are briefly described.

Task 1. Development of a finite-element method to model acoustic interactions: This can be considered as a structural-acoustic problem, where most tissue groups and surrounding water behave as acoustic fluids and bony tissues behave as elastic solids. In the modeling, the beaked whale is a structure represented by its morphometry (Task 2), where each anatomical part is assigned its own set of physical properties (Task 3). This work is being performed by Co-PI Feijoo.

Task 2. Morphometry and meshing the three-dimensional anatomy: These data will be acquired principally from CT scans performed at the WHOI Computerized Scanning and Imaging (CSI) Facility. Image data on cetacean specimens will be expressed in Digital Imaging and Communications in Medicine (DICOM) format. Amira visualization software will be used for segmentation and surface reconstruction. Automatic mesh generation will employ tetrahedral elements. CT data will be provided by WHOI Senior Scientist D. Ketten. Co-PI Reidenberg will be responsible for interpreting the anatomical data. Co-PI Feijoo will construct finite-element meshes from the anatomical data.

Task 3. Physical properties of tissues: The best available data will be used to represent the acoustically important properties of mass density, elastic constants, and absorption coefficients for each identified internal organ or other body part. This task will be led by the PI, with potential contributions of new *in vivo* data from P. Rogers at the Georgia Institute of Technology.

Task 4. Measuring interactions of acoustic fields with cetacean carcasses: In order to test the FEM code (Task 1), measurements will be performed of the internal pressure fields in instrumented marine mammal carcasses. Carcasses will be prepared by surgically implanting acoustic sensors; CT-scanned to determine sensor location and morphometry; then acoustically measured at NSWC. D. Ketten will perform the surgery and CT-scanning. Co-PI Rye will lead the measurement work at NSWC.

Task 5. Testing the FEM model: Rigorous testing will be performed by comparison with analytic solutions for immersed simple objects.

Task 6. Virtual Beaked Whale: This interactive online modeling and visualization system is the principal deliverable of the project. It incorporates a database with sets of whole-body morphometric data (Task 2) from beaked whales and other species, as well as the respective physical properties of tissues (Task 3). The output will consist of computed solutions for the internal pressure and displacement fields (Task 1). The user interface is being recommended by Co-PI Hastings. Co-PI Feijoo will direct programmers in design and implementation sub-tasks. Co-PI Hastings will also perform testing and quality assurance. The PI will coordinate the various sub-tasks.

WORK COMPLETED

Task 1: The present code development is particularly noteworthy for addressing two essential, intricate computational problems that have otherwise been neglected by the acoustic scattering community. One of these problems - the other is described under Task 2 - concerns the construction of software capable of efficiently solving structural acoustic problems with millions of degrees of freedom. This is required to solve problems involving acoustic interactions with heterogeneous structures and generic interfaces, e.g., marine mammals in their natural state of immersion. The associated FEM code, generically called the finite-element solver, is now capable of solving general structural-acoustic problems. This has incorporated earlier work implementing a perfectly matching layer, realizing acoustic and elastic elements and interface elements to transfer loads between these, and implementing a ten-node tetrahedral element for quadratic interpolation of the basic fields.

Task 2: The second essential and intricate computational problem that is being addressed concerns the creation of finite-element models that conform to tissue interfaces. This requires the use of unstructured meshes as opposed to rectangular, Cartesian grids. CT images must be segmented; surfaces between different, contiguous tissues must be triangulated; and the encapsulated volumes must be filled with volumetric elements, which are tetrahedral in this work for the sake of computational accuracy and efficiency. These volumetric elements are, moreover, being geometrically constrained to avoid extreme acute and obtuse shapes. Commercially available software, such as Amira (Visage Imaging, Inc., San Diego, CA), is powerful for segmentation and surface reconstruction, but inadequate for automatic generation of three-dimensional meshes, nor can it generate the meshes needed for defensible acoustic calculations, such as the creation of perfectly matched layers (PML), among other things. Three-dimensional visualizations and/or meshes have been prepared for each of three common dolphins, designated D-del40, D-del42, and D-del52. The carcass of D-del52 was used in the experiment described under Task 4. In addition, visualizations and meshes are being prepared for a minke whale head, in anticipation of modeling a virtual beaked whale.

Task 3: The subject of physical properties of marine mammal tissue has been discussed extensively by the Co-PIs, with important contributions and insights offered by D. Ketten and P. Rogers. It is clear that current knowledge of physical properties is mostly derived from *ex situ* measurements rather than the more desirable *in vivo* measurements. It is also appreciated that the physical properties of some tissues are influenced by pressure, e.g., the lungs and other air-containing tissues, by both pressure and temperature, as in the case of the melon. P. Rogers observed the experiment described under Task 4, with invitation to make measurements of physical properties with new *in vivo* instrumentation at the WHOI CSI Facility.

Task 4: A series of tests were performed in 2008 on tourmaline pressure sensors in a small laboratory tank and embedded in a 30-kg pig carcass. The usability of such sensors for measurement of internal pressure fields in ensonified mammalian carcasses was thus established. During the period 2-4

February 2009, the first experiment with a marine mammal carcass was performed at NSWC Carderock Division. The carcass was that of a young adult male common dolphin (*Delphinus delphis*), 119 kg, 211 cm total length, that had stranded and died on a Cape Cod beach two months previously. In the interim the carcass, designated D-del52, was stored at WHOI in a freezer at -20ºC. CT scans were obtained in the frozen state and following thawing to assess overall tissue condition. Tourmaline pressure sensors were surgically implanted in the blowhole, left lung, right lung, external right lung, melon, along right ear, epaxial muscle near the dorsal fin, and rectal abdomen. CT scans were repeated to determine the precise anatomical locations of the seven sensors. The carcass was transported in a chilled state to NSWC by car. On 3 February acoustic calibration data were collected on the external tourmaline sensors mounted on the suspension frame ensonified with a pair of ITC-1032 transducers arranged in a dipole-like configuration with a 15-cm rod separating the two. On 4 February the carcass was suspended within a PVC-pipe frame and immersed in the fresh water Blast Pond. It was exposed to multiple ensonifications by a single ITC-1032 spherical transducer. This was excited at each of three frequencies: 5, 7, and 10 kHz, by a 20-cycle sinusoidal burst with smooth rise and fall over two cycles, for each of three source locations: in front of the rostrum, and successively on the right and left sides of the carcass, with but different fore-aft and up-down locations. Data were recorded simultaneously on 15 channels from six external sensors, eight implanted sensors, and source transducer, over a total of 5 s for each frequency and source location, with 4-Hz pulse repetition frequency. Each signal was amplified by a PCB model 422E01 inverting-charge amplifier and digitized at 100 kHz. Noise data were also collected passively at the end of each series without source excitation. After the experiment, the carcass was removed from the suspension frame and transported by car to the Walter Reed Army Institute for Research (WRAIR), where a necropsy was performed, led by Dr. D. R. Ketten. Tissues were observed for trauma and samples collected for histological analysis. A WHOI CSI-Scanning and Necropsy Report was prepared. The acoustic data have been comprehensively reviewed within the MATLAB environment. Prominent noise at 60 Hz and sub-hertz frequencies, which is necessarily non-stationary owing to the short, 5-s data collection periods, has been removed by digital bandpass filtering with a 10% bandwidth. Qualitative conclusions are currently being supplemented by a detailed quantitative analysis.

Task 5: The FEM code described in Task 1 has been or is being benchmarked through a series of test computations. (1) Surface fields on the spherical shape due to plane-wave ensonification have been computed for each of two boundary conditions: pressure-release and rigid, for wavenumber-radius products over the range 0-15. Farfield backscattering cross sections have been computed on the basis of the surface fields and compared with known solutions. (2) Plane-wave-induced pressure fields in a fluid sphere with relative sound speed 0.8 and mass density equal to that of the immersion medium have been computed for wavenumber-radius products over the range 0-15. The reflectivity coefficient has been computed on the basis of the surface field and compared with the solution due initially to Anderson (1950). (3) Internal displacement and stress fields in a solid elastic sphere have been computed. The farfield scattering form function is being computed as a function of frequency for comparison with numerical results due initially to Faran (1951). Relative errors are being estimated for different mesh sizes relative to the acoustic wavelength. (4) Internal displacement and stress fields induced by spherical waves incident on elastic spherical and cylindrical shells are being computed.

Analytic solutions for the acoustic interaction of both plane and spherical acoustic waves in an absorbing fluid sphere immersed in a lossy immersion fluid have been developed and rendered in code for use in validating the FEM code. These solutions have been realized numerically for a 50-mm-diameter sphere ensonified at 10 and 100 kHz. The immersion medium has been represented as water of mass density 1000 kg/m^3, sound speed 1500 m/s, and variable absorption in the range 0-10

dB/wavelength. The sphere has been represented as a fluid with variable mass density over the range 500-2000 kg/m^3 to achieve density contrasts with water of 0.5-2, variable sound speed over 750-3000 m/s to achieve sound speed contrasts with water of 0.5-2, and variable absorption coefficient of 0 or 10 dB/wavelength. The pressure and displacement fields have been computed along the sphere axis, as defined by direction of propagation of the incident wave; transverse to this axis from center; and along the surface from the forward to reverse directions. In a special additional case, a focusing sphere with fluid mass density 1900 kg/m^3 and sound speed 857 m/s, the fields have also been computed with high precision at selected points for detailed comparison and assessment of computational accuracy. Preliminary documentation is contained in three abstracts (Foote 2007a,b, 2008).

Task 6: Visualization routines have been developed to return data from the FEM system and display these on a webpage. This system is operational in a pilot mode and is being used internally. Significant achievements include specification of the sonar frequency and direction of the incident plane wave, development of a client-server system that displays the computational results in the form of pressure fields in user-defined cross sections of the computational domain. The client-server system is responsible for passing data among the different components of the simulation environment, namely meshing, preprocessing, and FEM-analysis programs. The visualization system is presently based in MATLAB, and is capable of operating with meshes of up to two million elements. A new, successor system will be capable of operating with meshes with more than 20 million elements. A user group composed of colleagues from the international bioacoustics community is being defined for testing the Virtual Beak Whale when in a more advanced state.

RESULTS

The construction of a finite-element mesh is illustrated in Fig. 1 for a common dolphin. Detailed views of the tetrahedral meshes of both the skeleton and lungs and immersion medium are shown in Fig. 2. An interpretive three-dimensional surface rendering of the lower respiratory tract of the same specimen is shown in Fig. 3. The common dolphin carcass with implanted tourmaline sensors measured during the experiment on 4 February 2009 is shown in Fig. 4. An overview of the acoustic data collected during this experiment for a particular source configuration and transmit signal is shown in Fig. 5. These results are indicative of the qualitative findings of signals being registered in the blowhole, epaxial muscle near the dorsal fin, melon, and right lung. A benchmark solution for the pressure field induced by an external point acoustic source in a spherical elastic shell is visualized in Fig. 6. Another set of benchmark solutions are shown in Fig. 7.

IMPACT AND APPLICATIONS

National Security

At present, Navy operations at sea can be affected by the presence of marine mammals, hindering the use of sonar. The Virtual Beaked Whale will enable researchers to gauge the physical effects of particular sonar transmit signals on interactions with marine mammals.

Economic Development

Sonars, including echo sounders, are manufactured in the U.S. and in a number of other countries. Use of the Virtual Beaked Whale may suggest the value of using alternate transmit signal waveforms to mitigate possible harmful effects on marine mammals and other animals.

Quality of Life

An important tool in the assessment and management of fish stocks and ecosystems is acoustics. Safe operation of sonars and other active acoustic devices used in this work is essential. The Virtual Beaked Whale is expected to contribute to the process of ensuring safe acoustic operations.

Science Education and Communication

The new tool, the Virtual Beaked Whale, will be interactive. It is expected that the cumulative experience of users will contribute to new knowledge about acoustic interactions with marine mammals and other forms of aquatic life, also increasing public confidence in the value of data-based technology. The tool may be used by educators to promote education in fields as diverse as aquatic science, ecosystem assessment, resource conservation, and sonar engineering, also stimulating the kind of discussions that advance science.

RELATED PROJECTS

This project may benefit directly from a number of other projects. Three are cited. (1) Professor P. Rogers at Georgia Institute of Technology is currently investigating methods for determining elastic properties of cetacean head tissues *in vivo* under a grant from ONR. The quality of these will be unprecedented and of high value to the NOPP project. Discussions are underway with Rogers about measuring the properties of marine mammal tissues at the WHOI CSI Facility, mentioned under Task 3. (2) Dr. S. Ridgway of the U.S. Navy Marine Mammal Program and Dr. D. Houser of Biomimetica have provided morphometric data on a living bottlenose dolphin. (3) The Center for Ocean Sciences Education Excellence - New England (COSEE-NE) will be assisting the NOPP project in tailoring the interactive online tools under development to specific audiences. It will also be assisting in the dissemination of the results of the research and new educational tools.

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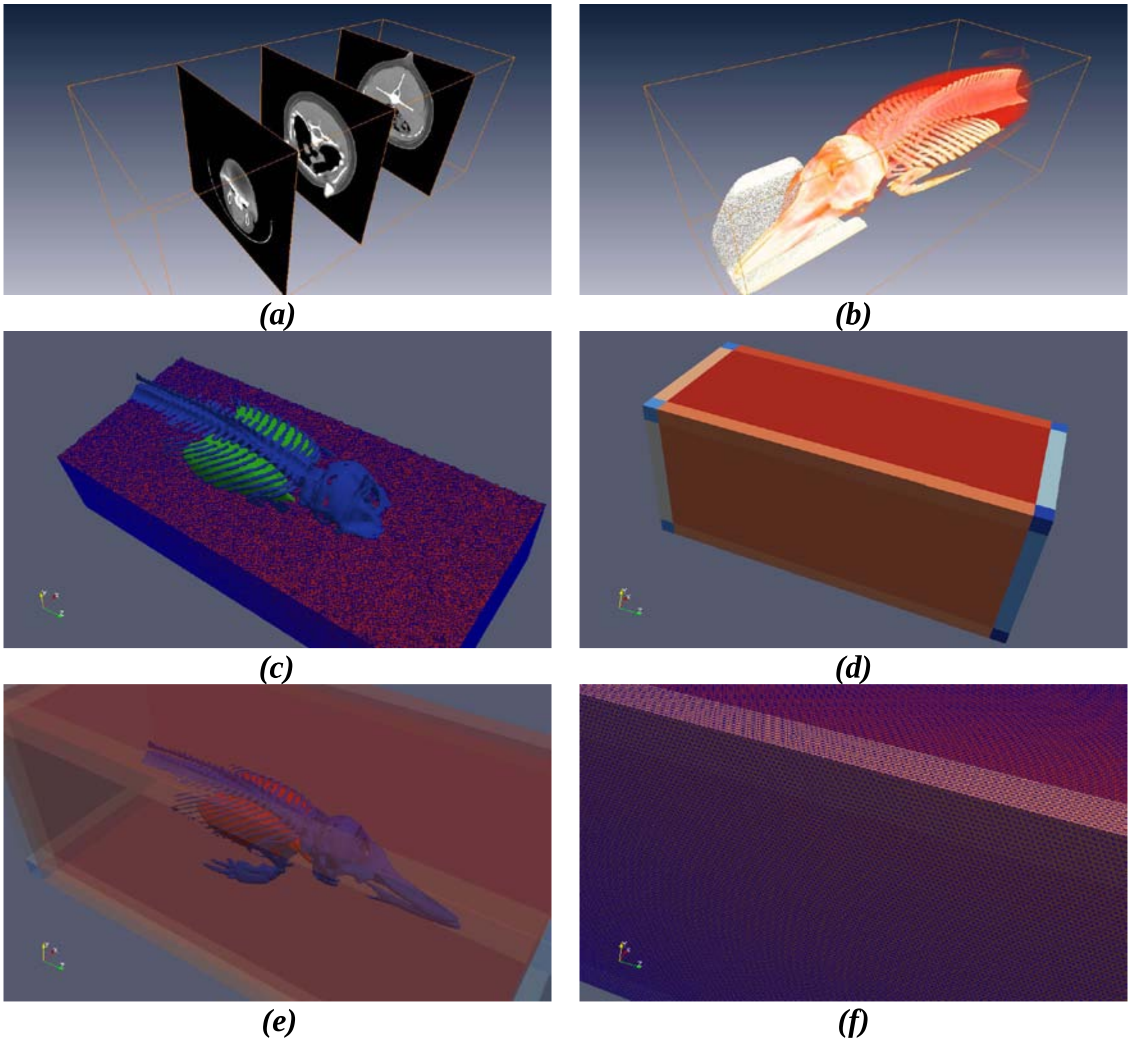
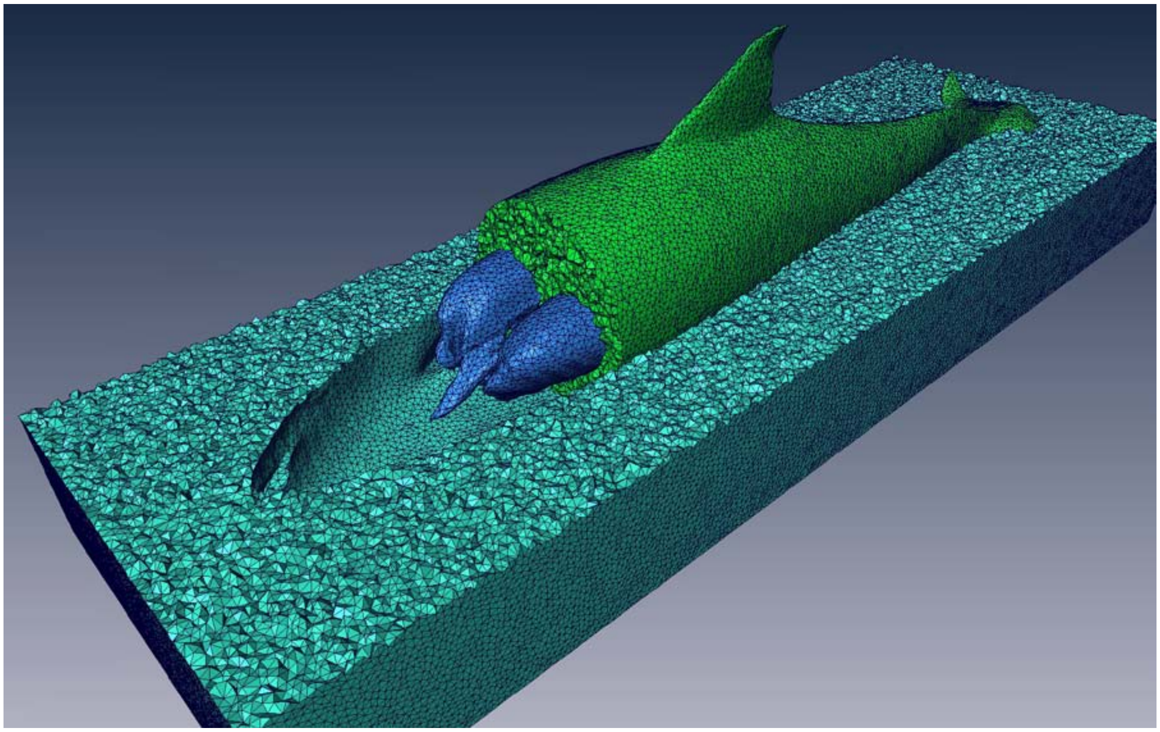
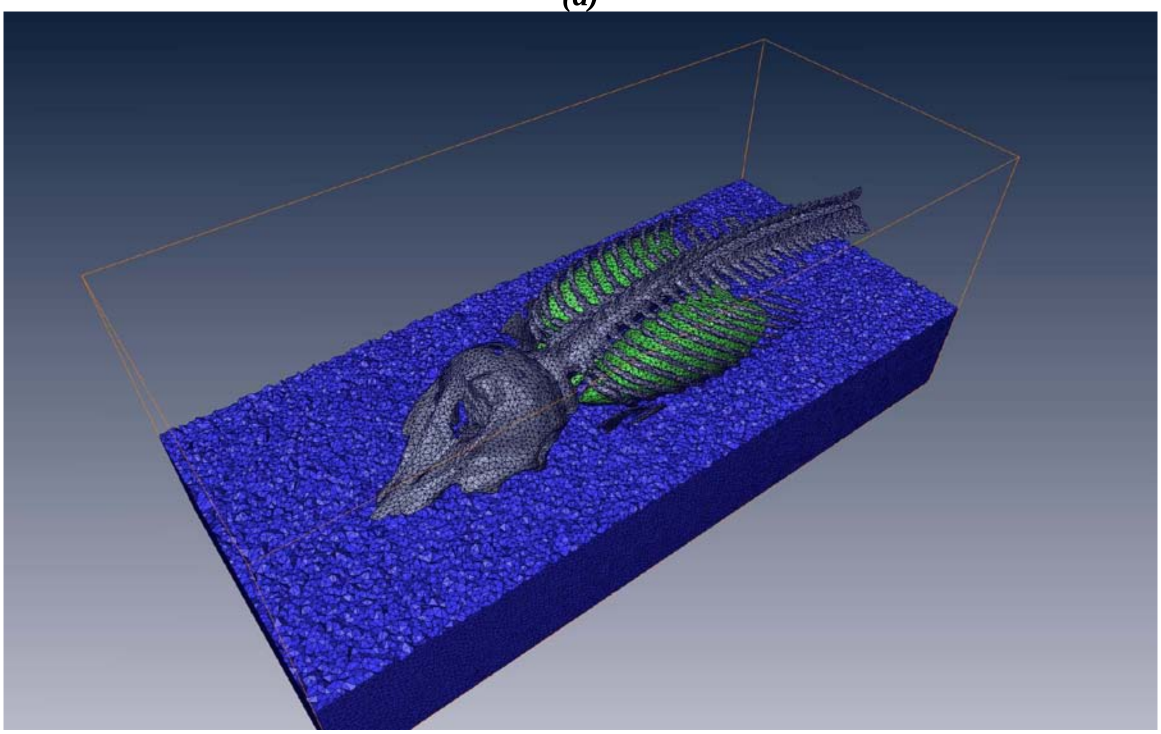


Fig. 1. Construction of the finite-element mesh for a common dolphin. From CT images (a), surface reconstructions of tissues can be obtained (b). These surfaces are sub-sampled and triangulations of the interfaces are created. From these triangulations, a tetrahedral mesh is created (c). An external mesh, which is necessary for acoustic computations, is constructed and joined with the previous mesh. An outline of the external mesh (d) shows different PML blocks in colors. The position of the animal within this mesh is shown in (e). A detail of the triangulation in the surface of the external mesh is shown in (f). Credit: G. Feijoo.



(a)



(b)

Fig. 2. Finite-element representation with tetraheda of a 142-cm-long common dolphin and external, computational volume, in two views. (a) The lungs are indicated in blue. (b) The skeleton is indicated in gray and the lungs in green. Credit: G. Feijoo.

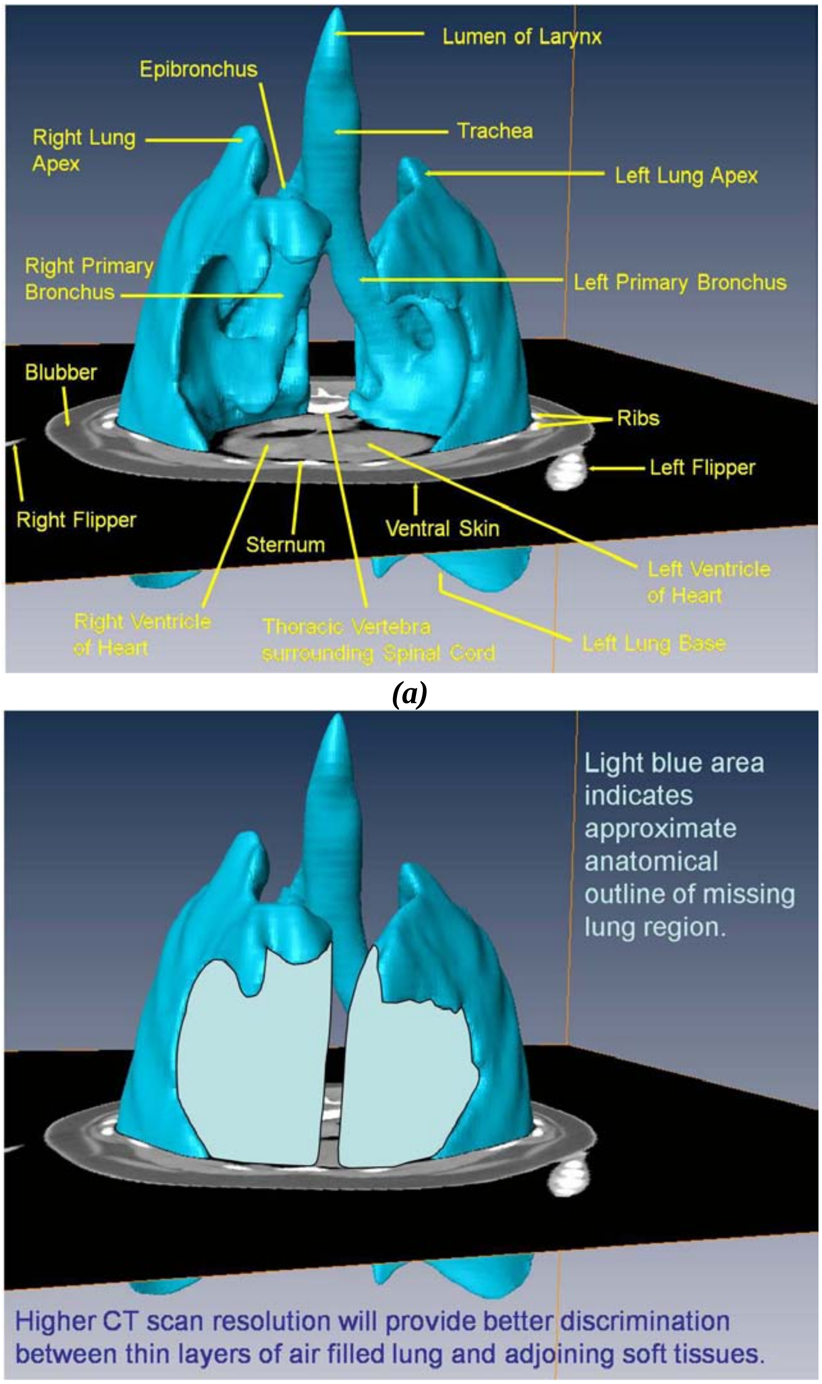
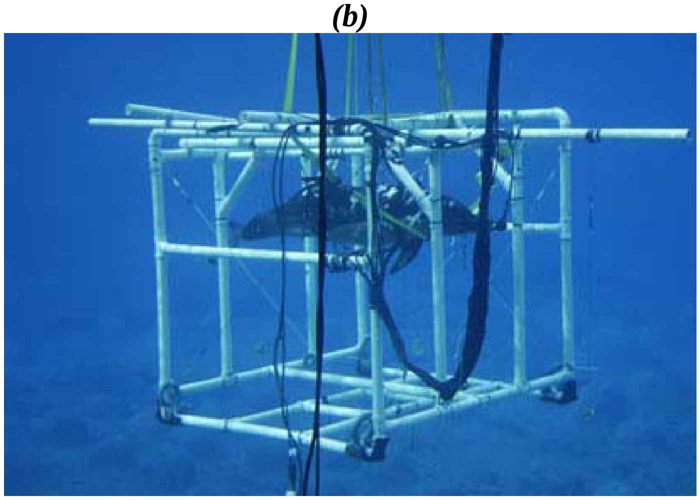


Fig. 3. Three-dimensional surface rendering, based on CT scans visualized with Amira, of the lower respiratory tract in a 142-cm-long common dolphin specimen, with superimposed transverse CT section. (a) Lower respiratory tract and nearby tissues are labeled. (b) Missing lung volumes are indicated. Credit: J. Reidenberg.

(a)

(b)



(c)

Fig. 4. Carcass of a common dolphin, 211 cm, 119 kg, following implantation of tourmaline sensors at the WHOI CSI Facility (a), suspended from a PVC-pipe frame at NSWC Carderock Division on 4 February 2009 (b), and immersed in the NSWC Blast Pond for acoustic measurement (c). Credit: D. Ketten, S. Cramer, K. Rye, W. H. Lewis, M. Hastings.

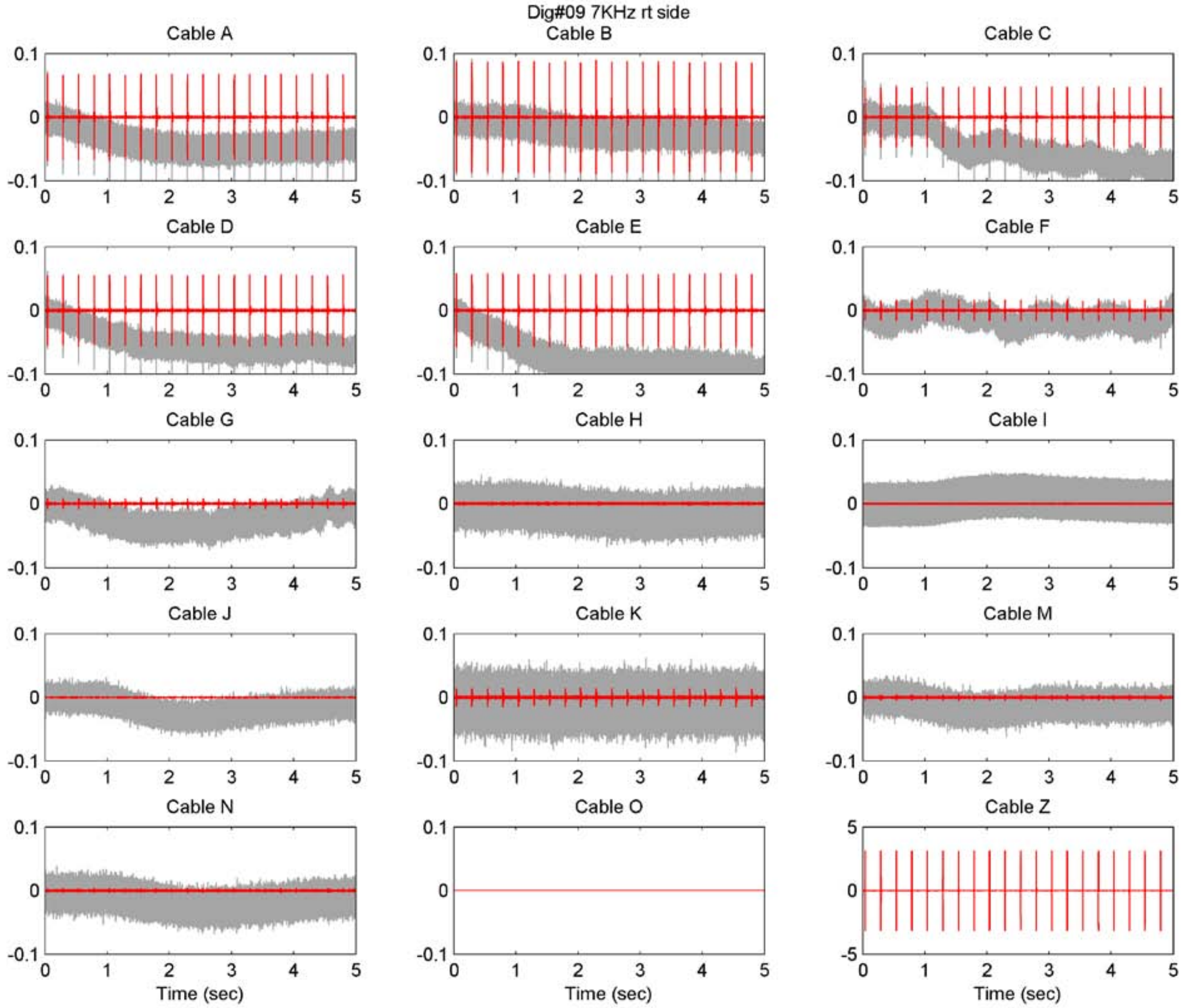


Fig. 5. Overview of acoustic data collected during the experiment with the common dolphin carcass at NSWC Carderock Division on 4 February 2009 with the ITC-1032 spherical transducer on the right side of the carcass and transmit signal centered at 7 kHz. The total data collection time is 5 s; the pulse repetition frequency is 4 Hz. The total signal, including background noise, is shown in gray. The signal resulting from digital bandpass filtering with bandwidth equal to 10% of the center frequency is shown in red. Cables A, B, C, D, E, and G are connected to external sensors. Implanted sensors are connected to Cable F for the epaxial muscle near the dorsal fin, Cable H for the left lung, Cable I for the external right lung, Cable J in the rectal abdomen, Cable K for the melon, Cable M for the left lung, Cable N for the right lung, and Cable O along the right ear. Credit: Y.-T. Lin, M. Hastings, K. Rye, K. Foote.

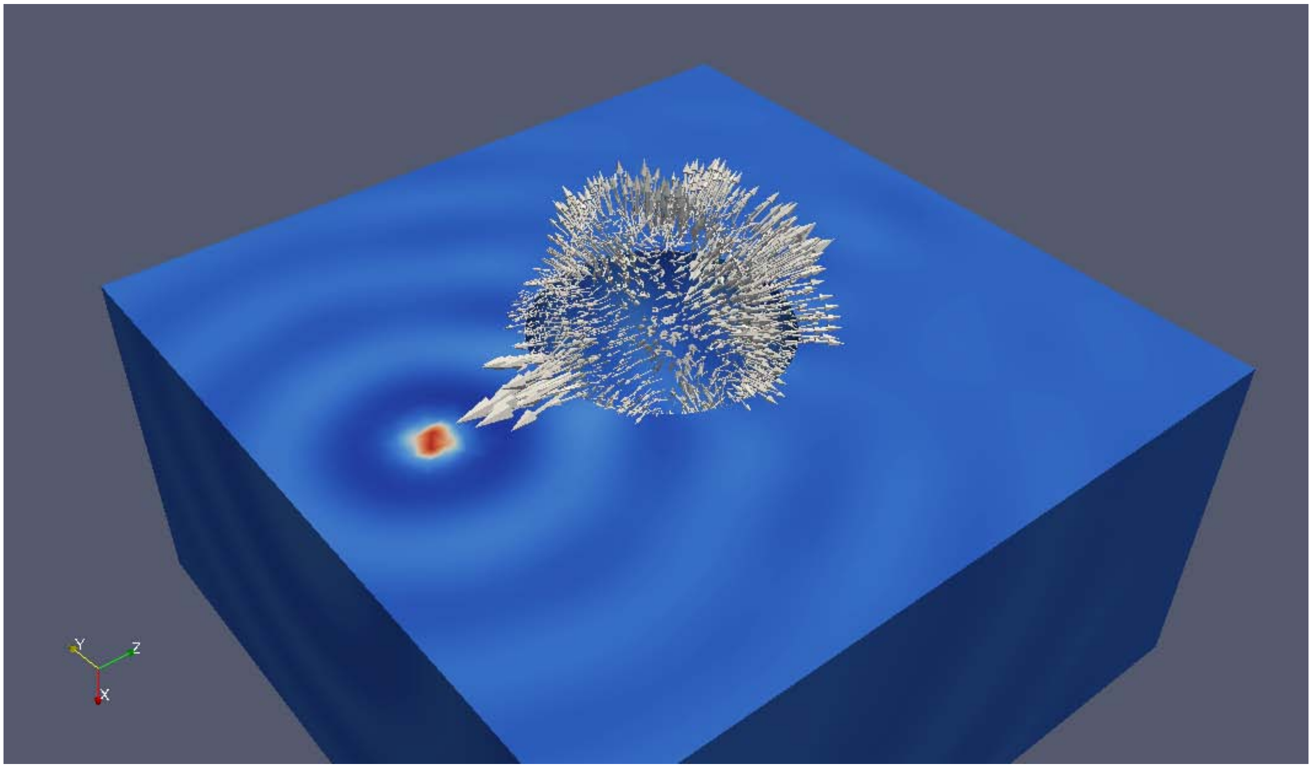


Fig. 6. Pressure field in water (colors) and velocity field (sub-sampled and displayed using arrows) induced in a spherical shell by a monopole source. The thin spherical shell was not rendered to permit visualization of the velocity field. Credit: G. Feijoo.

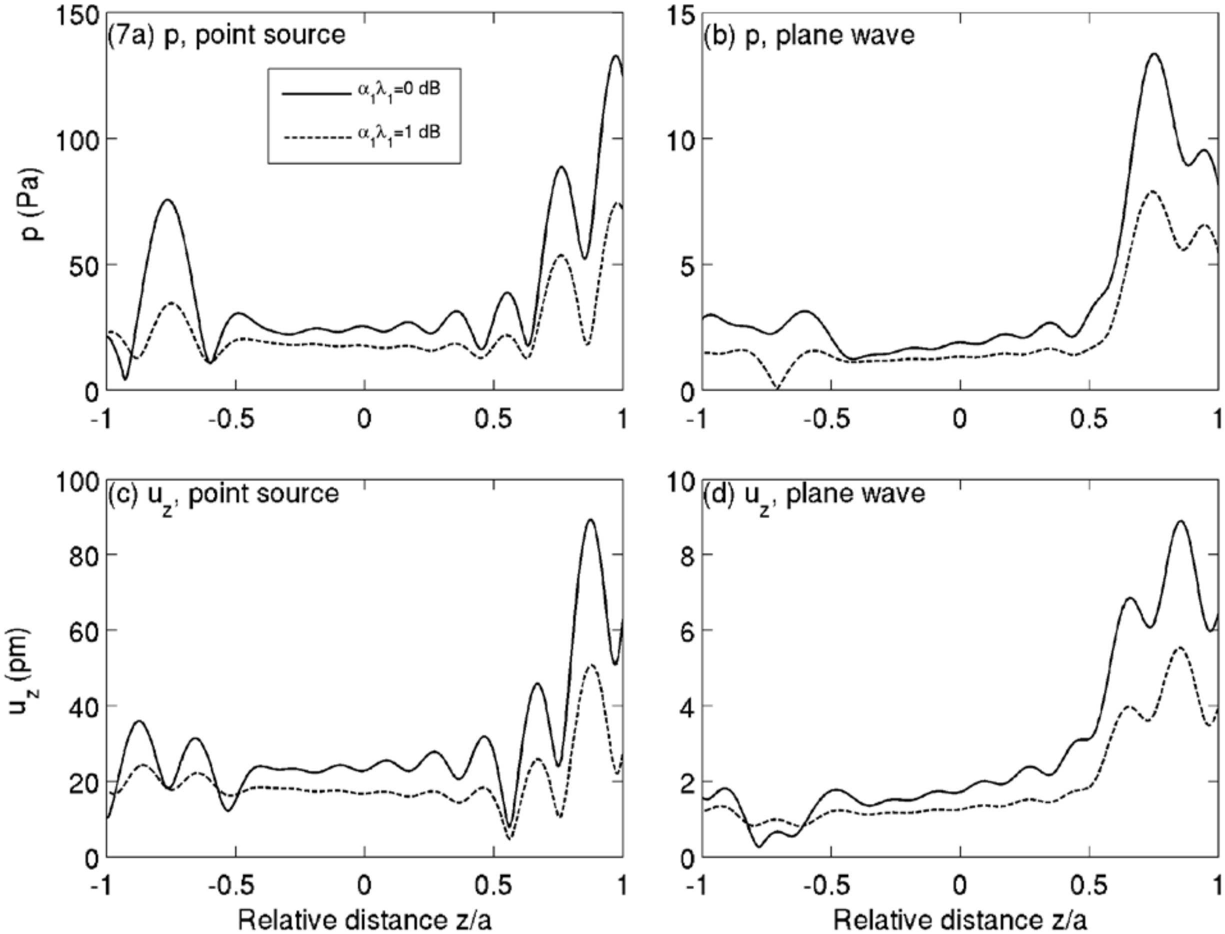


Fig. 7. Pressure and longitudinal particle displacement amplitudes along the longitudinal axis of an immersed 50-mm-diameter fluid sphere at 100 kHz due to ensonification by a spherical wave emanating from a point source of strength 1 Pa m at z=-75 mm on the same axis (a,c), and a plane wave of amplitude 1 Pa propagating in the positive z-direction (b,d). The mass density of the fluid sphere is 1900 kg/m^3, sound speed, 857 m/s, and absorption coefficient, α_1, 0 or 1 dB per internal wavelength. The mass density of the immersion medium is 1000 kg/m^3, sound speed, 1500 m/s, and absorption coefficient, 0 dB/m. Credit: K. Foote.